Memoirs of the Indian Meteorological Department.

VOL. XXI, PART XIII.

ON THE CALCUTTA STANDARD BAROMETER.

BY

E. P. HARRISON, PH. D., F.R.S.E.

UNDER THE DIRECTION OF

GILBERT T. WALKER, C.S.I., M.A., Sc.D., F.R.S.
DIRECTOR-GENERAL OF OBSERVATORIES.

Published by order of His Excellency the Viceroy and Governor-General of India in Council.

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On the Calcutta Standard Barometer, by E. P. Harrison, Ph. D., F.R.S.E.

The Standard Barometer, shown diagramatically in Fig. 1, was used in conjunction with a standard nickel steel scale, the observing instrument being a cathetometer by Casella fitted with one telescope and a micrometer eye-piece. Three glass pointers are sealed into the bulb R, as shown in Fig. 1, and the mercury can be adjusted by means of a moveable system S to touch one or other of the pointers in the bulb R. A lower steel pointer C can be "set" in the mercury surface of T.

The instrument was filled with mercury by Mr. J. H. Field in the Physical Laboratory at Presidency College, Calcutta, by kind permission of the Principal, using a Gaede mercury pump and an induction coil belonging to the College. Glass sealed joints were used throughout to connect the barometer tube, a P_2O_5 drying bulb and a vacuum tube, and this system was connected to the Gaede pump by a glass ground joint and mercury seal.

The filling was effected in nine stages with specially pure mercury supplied as "Electrically prepared" by the makers of the barometer, the Société Genevoise; and the exhaustion was carried sufficiently far at each stage, after boiling the mercury already put in, to show cathode rays in the vacuum tube worked by the induction coil. The exhaustion was therefore certainly as high as ·001 mm. of mercury during filling, and on subsequently letting down the mercury, when the instrument was erected the vacuum would reach a still higher value, and retain it subject only to the effect of any slow exudation of gases from the walls of the tube in course of time.

The fine adjustment of the level of mercury in the barometer as supplied by the maker was effected by turning a screw-head near the cylinder S, Fig. 1, but in practice it was found impossible to use this with accuracy, since the very small but unavoidable vibrations set up thereby on the mercury surface caused premature conjunction between mercury and pointer, and such conjunctions resist a lowering of the mercury by certainly as much as ·002″ without rupture.

It was therefore found necessary to attach to S another cylinder (not shown in Fig. 1), the mercury in which was connected with that in S by a U tube, and to dip into the new mercury a loaded glass tube (sealed full of mercury) to a variable depth. The extent of dipping was controlled through a length of silk cord by a fine screw from the cathetometer, so that while watching for conjunction through the telescope, the observer himself was able to do the regulation. Apart from this detail the barometer was erected in the manner intended by the maker.

The barometer with its fittings, covered by a glass case, was mounted on the wall of an inner windowless room whose temperature variations were usually small. General illumination was obtained from three 16-c.p. electric lamps, while for lighting the scale, two small lamps mounted on an adjustable frame and placed 30 inches apart in a vertical line, were found extremely useful.

Preliminary Adjustments.

The cathetometer telescope having been focussed on one of the upper pointers in the barometer tube, the standard scale and lights were adjusted so that on rotating the

Barometer No. 712 by Casella which was to be compared with the standard was in a separate room. The whole instrument was thickly lagged with cotton wool throughout its length, observation windows being left at the Fortin point, the top of the column and at the reading point of the attached thermometer; the bulb of the latter was immersed in mercury. Illumination was effected through other small holes by means of electric lamps.

In making a comparison observations of No. 712 were taken every ten minutes, beginning about an hour before the actual time of comparison decided on; 15 minutes before this No. 712 was read every five minutes and the observations continued for about half an hour after the completion of the standard barometer measurements.

All the readings of No. 712 thus obtained having been reduced to 32° F the results were plotted against the time. It is then obvious that if the corrected height of the standard barometer at the "instant of setting" is known, the comparison can be effected by reading off the pressure shown by No. 712 from the graph at this instant.

ERRORS.

A. Due to temperature changes in :—

(1) brass, glass and mercury during the "setting" and before the reading of the pointers.

(2) the brass frame, affecting the distance between the pointers after "setting" and before the final reading.

(3) the scale itself after "setting" and before reading.

B. Due to change in the pressure during a "setting."

C. Due to refraction, owing to the glass of the top cylinder being of irregular thickness, the irregularity being caused by the sealing in of the three pointers.

D. Due to refraction, owing to the cylinders not being vertical.

E. Due to the vapour pressure of mercury.

F. Due to the presence of residual air above the column.

G. Due to graduation errors in the Standard invar scale and to an error on its length due to its temperature being different from 0° C.

A

(1) *During "setting."*—Referring to Fig. 1 and assuming the support to be entirely at B* let the rise of temperature be 1 deg. C, in the interval between setting the top and bottom pointers. The only change of mercury level due to this rise which needs to be considered is in the top cylinder only, after "setting" on one of the upper pointers.

Let V be the total volume of mercury in the instrument, A_1 be the area of the cylinder S.

* This is probably the case, since the leather pad under the tube at D is loose.

telescope to view the scale, the divisions of the latter were clearly visible and sharply in focus. The lower pointer was then brought into focus and into a vertical line with the upper one by means of its adjusting screw.

The magnification factor, f, of the micrometer eye-piece was determined by finding the value in micrometer scale divisions of one-tenth and one-twentieth of an inch on the standard scale.

Mean value or magnification adopted was 0·0331 ins. ≡ one micrometer comb division ≡ one complete turn of the screw-head. By the method of reading employed, the zero error of the micrometer was not involved.

The temperature was determined by two thermometers graduated to 1-10th degree C, placed in the positions shown in Fig. 1. They were immersed in mercury contained in glass tubes of approximately the same size and thickness as the barometer tube near the centre of the column, and were read by means of two reading telescopes.

The corrections of the thermometers were determined against the Alipore Standard, and are given in Table 1.

General method adopted during a measurement of Barometric height.

In making a determination of the barometric height the general plan was to start all the lights two or three hours before the time decided on for the measurement. Previous experiment proved that this interval was sufficient to ensure that the temperature of the apparatus, slightly raised by the lamps in its neighbourhood, had become steady.

Five-minute or ten-minute readings of the two thermometers were continued from the moment of lighting the lamps until the end of the experiment, and these values plotted on curve paper.

When all was steady, the mercury column, previously adjusted roughly, was raised by a second observer with the help of the fine adjustment already referred to on page 119 until, as seen through the telescope (see page 126, foot-note), the upper pointer and its image in the mercury surface were just in contact. The time of contact was then noted and the cathetometer telescope placed to observe the lower pointer. The latter was lowered by its screw adjustment until it in turn was in contact with its own image, the time of contact being noted as before.

The operation of "setting" just described usually occupied from 30 secs. to one minute, and the "time of setting" adopted for calculation was the mean time of setting for top and bottom pointers.

Immediately after "setting," the mercury was lowered so as to leave the pointers free for reading.

The fixed micrometer thread was then adjusted on the tip of the bottom pointer, the telescope turned to view the standard scale and the distance of the fixed thread from the nearest scale division read off on the micrometer head. The mean of 7 readings of this distance was adopted.

Finally the telescope was raised and the corresponding process gone through for the upper pointer.

The times of beginning and ending the pointer readings were recorded in every experiment in order to facilitate subsequent temperature correction.

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Let V be the total volume of mercury in the instrument, A_1 be the area of the cylinder S.

* This is probably the case, since the leather pad under the tube at D is loose.

A_2 be the area of each of the cylinders R or T (equal).

As the apparatus is arranged $A_1 = 2A_2$

α_1 = the coefficient of linear expansion of brass $= 19 \times 10^{-6}$

α_2 = the coefficient of cubical expansion of glass $= 25 \times 10^{-6}$

α_3 = the coefficient of linear expansion of glass $= 8 \times 10^{-6}$

α_4 = the coefficient of linear expansion of steel $= 11 \times 10^{-6}$

α_5 = the coefficient of cubical expansion of mercury $= 180 \times 10^{-6}$

k = the ratio of the area of the narrow tube at E to the combined area of the three wide cylinders.

Let the temperatures at the beginning and end of the setting be d and d + δ; the change in the interval may be regarded as taking place in three stages: in the first every part of the barometer is supposed to have the expansion coefficient of glass, in the second the mercury expands with the coefficient $(\alpha_5 - \alpha_2)$ to its final amount, and in the third the base of the cylinder S is lowered a distance

$$(l_1 + l_4)(\alpha_1 - \alpha_3)\,\delta.$$

During the first two stages the mercury will rise a distance x in R and that in S and T will rise $x - b\alpha_5\,\delta$ where b is the height of the barometer and x is given by an equation for the change in volume

$$V\alpha_2\,\delta + (x - h\alpha_3\,\delta)\,A_2 + (x - b\alpha_5\,\delta + \overline{l_1 + l_3}\,\alpha_3\,\delta)\,(A_2 + A_1 - 2\,k\,A_1) = V\alpha_5\,\delta$$

where h is the height of the mercury surface in R above the point B.

During the third stage the mercury will rise y in R, S and T, where

$$y\,(A_2 + A_2 + A_1 - 2\,k\,A_1) + A_1\,(l_1 + l_4)\,(\alpha_1 - \alpha_3)\,\delta = 0$$

The total absolute rise $(x + y)$ corresponds to the temperature d + δ, so that the rise when referred to the mean temperature d + $\frac{1}{2}\delta$ will be, relative to the glass pointer, $x + y - \frac{1}{2}\,b\alpha_5\,\delta - h\alpha_3\,\delta$.

Now V is approximately 300 c.c., A_1 is 25 sq. cms., k is ·025 and the corresponding rise for 1°C is found to be + ·0013 inch.

(2) *After "setting" up to mean time of reading pointers.*—

Error due to temperature change in brass frame only.

Assume support is entirely at B.

For 1° change of temperature the lower end of the lower pointer has fallen by

$$l_1\,\alpha_1 + l_3\,\alpha_4 = (53\times19+14\times11)\,10^{-6}\text{ cms.}$$

Hence the correction to the barometer height in this account is= —·00046 inch per degree C.

(3) The invar scale has a temperature coefficient which gives rise to an error due to expansion of the scale for which the appropriate correction is +·00011 inch per 1° C rise of temperature (from Table 2, p. 129).

B

Suppose the pressure to be rising δ inches per minute and that a "setting" occupies one minute. Let the setting on the top pointer occur at time t and the setting of the lower pointer at time t′. Then (fig. 2) if A is the level of the top pointer and B

the position of the mercury in the lower cylinder at time t, H_t is the true height of the barometer at that instant.

Later, at time t′ the position of the mercury is A′ in the top cylinder and B′ in the bottom cylinder, the true height being $H_{t'}$.

The actual height observed is $AB' = h$.

Now in a determination of barometric height we assume the pressure at the mean time of setting $\frac{t+t'}{2}$ to be represented by h; that is, (since the pressure may be regarded as changing uniformly with the time over a small range) we assume the mean true pressure $\frac{H_t+H_{t'}}{2}$ to be represented by h.

Hence to find the error involved in a change of pressure during setting we have to find the value of $\frac{H_t+H_{t'}}{2} - h$ ... ... (1)

in terms of δ

From fig. 2 we have $h = H_t + x_1$ ... ... (2)

also $H_{t'} = H_t + x_1 + x_2$ ... ... (3)

while from the relation between the areas of S. R. and T. (fig. 1) $x_2 = 3x_1$

whence from (2) and (3) $h = \frac{3H_t+H_{t'}}{4}$

Therefore, remembering that $\delta = H_{t'} - H_t$

expression (1) becomes $+\frac{1}{4}\delta$.

The most rapid change of pressure per minute during any experiment was about 0·0004 inch, therefore the correction to the height due to the use of h instead of $\frac{H_{t'}+H_t}{2}$ when the pressure is rising is $+ 1/4 \ (0{\cdot}0004) = + 0{\cdot}0001$ inch when a "setting" occupies one minute.

Usually the pressure was changing about 1/4 as rapidly as this giving a correction of + ·00002.

C

This appeared at the outset to be important.

It was obvious by inspection that some error of the kind must be involved, since the sides of the top cylinder near the pointers were noticeably irregular. Subsequent experiment confirmed this view.

It was decided to try to obtain an estimate of the order of the error by measuring directly the thickness of the barometer tube at various points along its length, (*a*) near a pointer, (*b*) away from a pointer.

The tube chosen for measurement was a duplicate supplied with the apparatus and was not the actual barometer tube as now set up.

Let fig. 3 represent a vertical median section o the tube wall.

P the position of one of the pointers.

T the position of the focal plane of the telescope.

A the angle of the very thin prism involved.

y the displacement of P.

x the radius of the tube = 2 cms.

Then if the thickness of the glass is d_1 and d_2 measured at two points r cms. apart

$$\tan A = \frac{d_2 - d_1}{r} = \frac{d}{r} \text{ (say)}$$

Therefore the deviation (A small) $= \phi = (\mu - 1) \tan^{-1} \frac{d}{r}$ also $\phi = \tan^{-1} \frac{y}{x}$ approximately.

$$\therefore \; y = x \tan\left[(\mu-1) \tan^{-1}\frac{d}{r}\right] = 2 \tan\left[\tfrac{1}{2} \tan^{-1}\frac{d}{r}\right] = \frac{d}{r} \text{ cms. approximately} \quad \ldots \quad \ldots \quad (4)$$

The value of $\frac{d}{r}$ was found by means of a reading microscope first focussed on the inside surface of the tube and then on the outside surface at several places along the tube μ was assumed to be 1·5.

The focussing was effected with considerable accuracy owing to a slight devitrification of the glass which had occurred, also to the presence of the microscopic fungus so commonly seen on old glass in this climate. To give an idea of the limit of accuracy of these measurements a few of the numerical data are quoted in full (see Table 3). The results of all the measurements are set out graphically in fig. 5.

There is a marked difference between the uniformity of thickness in the neighbourhood of the pointer and in the portion of the tube away from a pointer.

Taking a value of d over a range of 1 mm. near the pointer tip, we get

values of $\frac{d}{r}$ varying from 0 to ·04″

whence from equation 4 y varies between 0 and ·04″ the maximum occurring in the immediate neighbourhood of the place where the pointer is sealed into the tube. So that if the lower cylinder is regarded as having parallel sides it is *possible* for an error of the order of 0·04 inch to occur in the observed barometer height due to the refraction effect discussed in this paragraph.

Errors as large as this are however unlikely since the pointer tip is at a level in the tube about 2 cms. below the glass seal. It will be seen below (p. 126) that an error of ·014″ or about $\frac{1}{3}$rd of the calculated maximum error was actually detected experimentally between heights determined by setting on the middle pointer through different portions of the glass (telescope not horizontal). Between measurements made by setting on any one pointer through practically the same portion of glass (telescope horizontal) it seems likely that the refraction error may be as great as ± ·005″.

This estimate is obtained by considering the largest differences between individual determinations of the barometer height, when the telescope was horizontal.

D

If a cylinder is not vertical but is inclined $\theta°$ away from the telescope (fig. 4); let "a" be the thickness of the glass, ϕ the angle of refraction and "d" the vertical displacement produced, then we have,

required correction to the height $= d = a\,(\theta - \phi)$

$$= a\,\theta\,(1 - \frac{1}{\mu})$$

In the barometer as set up, the top cylinder appears to be vertical while the lower one leans back just perceptibly from the telescope. It is hard to determine the inclination exactly but it cannot exceed 2°.

In that case since

$$a = \cdot 1 \text{ cm.}$$
$$\mu = 1\cdot 5.$$

We have

$$d = \frac{2 \times \cdot 1 \times \cdot 33}{57\cdot 3}$$
$$= -\cdot 0004 \text{ inch.}$$

E

According to the most recent determinations the vapour pressure of mercury at 30 deg. C is not greater than 0·0002 inch, giving a positive correction of this amount.

F

The question of this residual air is dealt with on p. 127.

G

The combined correction due to graduation and temperature error is + ·0000 inch assuming the scale to be at 30° C.

Collecting these corrections and assuming the temperature rises 0·2° C during "setting" and again 0·2° C between "setting" and the reading, we find the combined effect of A B D E and G to be + ·0010".

The following is an example of a single comparison in detail :—

October the 9th.	Mercury set on lowest of the three top pointers. H.	M.	S.
Time of setting, top	9	6	40
Time of setting, bottom	9	7	15
Mean time of setting	9	6	57
Time of bottom scale, reading begins	9	8	40
" " ends	9	12	40
Time of top scale, reading begins	9	13	10
" " ends	9	14	50

f = magnification factor = ·0331 inch.

Top. Scale.	Top. Micrometer divisions.	Bottom. Scale.	Bottom. Micrometer divisions.
32,55 +	0·250	2,75 +	1·260
	0·253		1·252
	0·240		1·240
	0·250		1·250
	0·253		1·265
	0·250		1·275
	0·245		
Mean	0·2487	Mean	1·2[illegible]

Uncorrected height 32·85 —2·75—(1·2620—0·2487) f=30·0665 inches.

Mean temperature (corrected) of top and bottom thermometers at time 9h 6′ 57″ (from graph described on p. 120)

=30° 285 C =86°·513 F.

Height reduced to 32° F=29·9024 inches.*

Reading of barometer 712 at time 9h 6′ 57″(from graph described on p. 121 reduced to 32° F.

=29·8973 inches.

Corrected for level 29·8983 inches.

DIFFERENCE, Standard bar —No. 712=0·0041 inch, uncorrected for A,B,C,D,E,F and G.

List of Comparisons.

The following table gives the results of the comparisons :—

Date.	Standard reduced to mercury at 32° F.	No. 712 reduced to 32° F (scale assumed correct at 62° F) and corrected for level difference.	Difference Standard No. 712 in inches.
Lowest pointer—			
January 25	29·9691	29·9650	0·0041
January 25	29·9696	29·9650	0·0046
October 9	29·9026	29·8983	0·0043
. . . .	29·8760	29·8730	0·0030
. . . .	29·8726	29·8665	0·0061
. . . .	29·8627	29·8590	0·0037
. . . .	29·8640	29·8570	0·0070
November 2 . . .	29·9295	29·9230	0·0065
		Mean .	0·0059
	or adding the correction (p. 125) .		+0·0010
			+0·0069
Middle pointer—			
*October 15	29·9113	29·8960	0·015
* „ 15	29·9087	29·8918	0·017
* „ 23	29·9557	29·9540	0·002
October 25	30·0719	30·0650	0·0069
„ 25	30·0673	30·0618	0·0055
November 2	29·9235	29·9170	0·0065
„ 2	29·9252	29·9190	0·0060
„ 2	29·9242	29·9180	0·0062
		Mean .	0·0062
giving a mean value of ·0070	adding the correction .		+0·0010
			+0·0072

* Coeff. of Expansion of mercury for this calculation was taken to be 0·0001010 per degree Fahrenheit.

The three values marked with an asterisk which are excluded from the mean were obtained by "setting" with the telescope sighting downwards on the mercury, *i.e.*, the pointer and its image were seen through a different portion of the glass than when the telescope was horizontal during the reading of the pointers. This evidently introduces a large refraction error. All other "settings" were made with a horizontal telescope.

No measurements were made using the top pointer in the upper cylinder; nothing was to be gained by such measurements, seeing that the unknown refraction error was larger than the residual air error.

Estimate of the Probable Error.

In taking a complete reading of the position of the mercury the following operations are involved; each operation may be regarded as possessing a separate probable error.

(1) P. E. of a single setting of the mercury on the pointer.

(2) P. E. of a single setting of the cross wire on the pointer.

In addition there is involved

(3) P. E. of the mean of the scale readings of a particular setting.

(1) can be estimated from a series of measurements of the height of the pointer as read on the scale.

It is found to be $= \cdot 0004$ inch.

(2) may be taken as having the same value as (1).

(3) is found to be $= \cdot 00014$ inch.

Hence the P. E. of a complete observation of the top of the column may be reasonably taken as ·00094″ say ·001″.

Similarly for the complete observations of the bottom of the column.

Hence the P. E. of a single reading of the height

$$= \sqrt{2\,(\cdot 001)^2}$$
$$= \cdot 0014 \text{ inch.}$$

Evidently the refraction error C is the largest of all the errors and is unfortunately not to be ascertained with exactness. Its existence affords the most likely explanation of the fact that a larger value for the mean difference (Standard — 712) is obtained when the space above the mercury is small than when it is large. The observations (middle pointer) of October 15 and October 23 in which settings were made through different positions of the glass tube, indicate how great is the possible error due to refraction.

On account of the refraction error, the question of residual air must also remain indeterminate, though the method of filling renders it reasonable to assume the residual air pressure as less than ·0001 when the lowest of the three pointers is used in a height measurement.

Result of the Comparison.

Using the mean corrected value given on p. 126 we have the difference (neglecting the estimated refraction error)

Calcutta Standard—No. 712 = + ·0070 ±·0014.
But Kew Standard—No. 712 = + ·008″.

∴ Kew—Calcutta Standard = —·001″ ±·001, a result which indicates so far as it goes that there is no important difference between the Kew and this new Calcutta Standard.

If the refraction error is taken as $\pm$·005 it follows that the determination of Kew—Calcutta is probably correct only to ·01″ which is an error larger than the difference to be observed.

The present investigation confirms the remarks made by B. F. E. Keeling (in the Meteorological Report of the Survey Department, Egypt) that the accuracy obtainable with the Geneva type of barometer is limited chiefly by an unknown refraction error. It is clear that a completely new type of tube, possibly combined with a new method of measuring the height of the mercury, is necessary if greater accuracy is desired.

In conclusion I would like to express my thanks to Babu Dwijendra Kumar Mazumdar, M.A., Demonstrator in Physics at the Presidency College, Calcutta, and to Babus Nibaran Chandra Biswas and Bijoy Krishna Roy, M.Sc., Observers at the Alipore Observatory, for valuable help given when making the comparisons.

TABLE 1.

Thermometer Errors (between 20°C and 32°C).

Top thermometer.		Bottom thermometer.	
At 20°C	+·07	At 20°C	+·10
„ 28°C	+·09	„ 28°C	+·12
„ 33°C	+·08	„ 33°C	+·10
„ 0°C	+·10	„ 0°C	+·10

TABLE 2.

Corrections of the Invar Scale.

The distance between 0 and 36 on the scale is 35·99723 inches.

The temperature correction is

$$L_t = L_0[1 + (3{\cdot}634t - 0{\cdot}00561t^2)10^{-6}]$$

This gives for L=30″

t	Correction with L=30″.
	″
20°C	+·0021
25°C	+·0026
30°C	+·0031
35°C	+·0036

The corrections to be applied to the scale are

Division.	Correction.	Division.	Correction.	Division.	Correction.
	"		"		
0	·0000	12	—·0008	30	—·0019
1	·0000	18	—·0011	31	—·0020
2	·0000	24	—·0016	32	—·0022
3	—·0001			33	—·0022
4	—·0002			34	—·0024
5	—·0002			35	—·0025
6	—·0003			36	—·0025

Table 3.

Tube horizontal. Readings near tip of middle pointer.

Microscope horizontal reading.	Inner surface reading.	Outer surface reading.	Mean difference in cms.	Thickness of the glass.
8·7 . . .	8·771	8·844	...	...
	8·771	8·842	...	...
	8·771	8·845	...	...
	8·767	8·840	...	...
	8·770	8·843	...	...
Mean . . .	8·7700	8·8428	·0728	·1102
9·0 . . .	8·766	8·843	...	...
	8·767	8·841	...	...
	8·766	8·841	...	...
	8·768	8·840	...	...
	8·766	8·842	...	...
Mean . . .	8·7666	8·8418	·0752	·1128

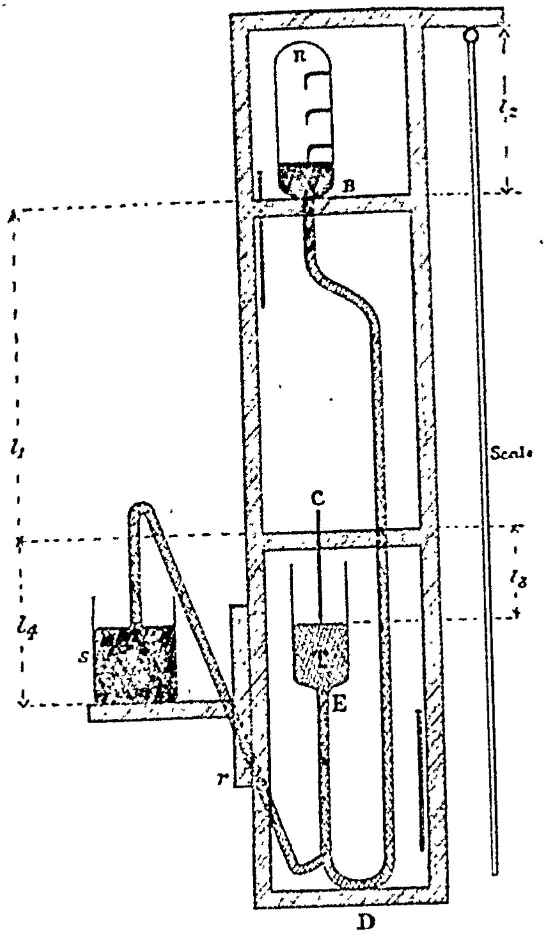

Fig. 1.

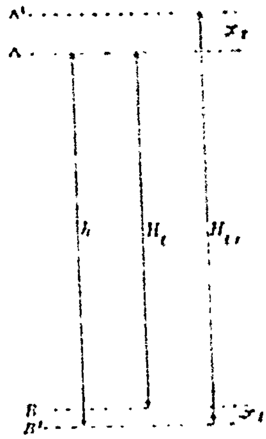

Fig 2.

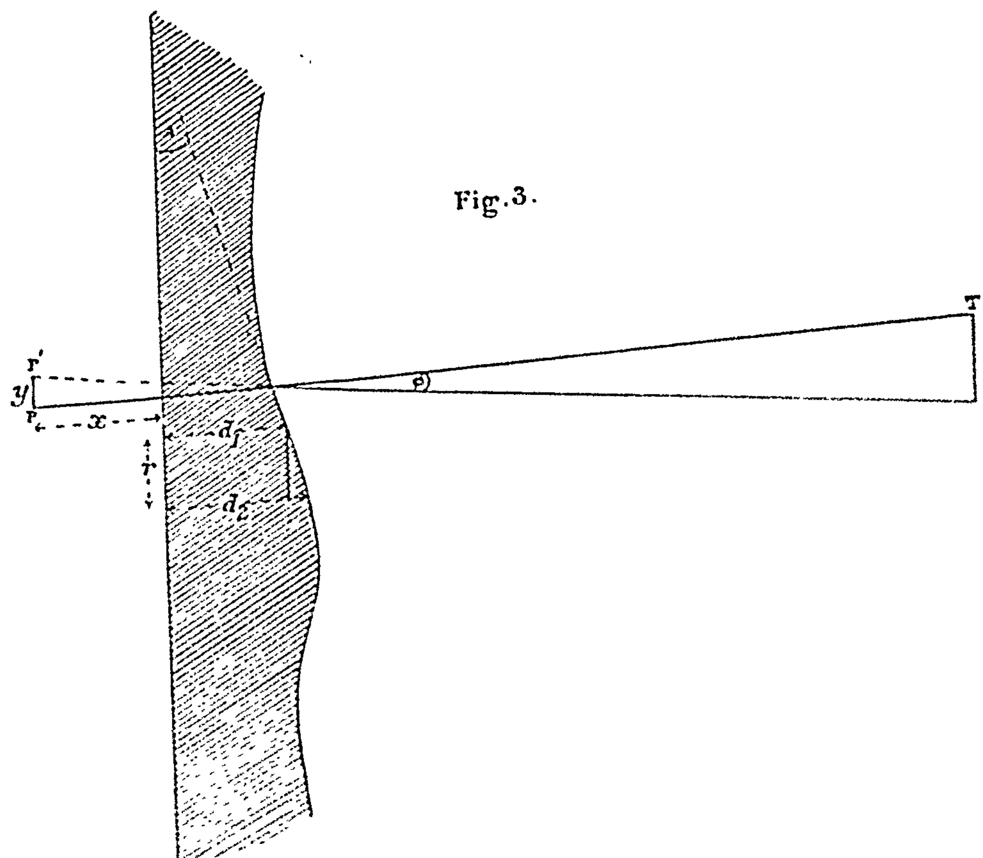

Fig.3.

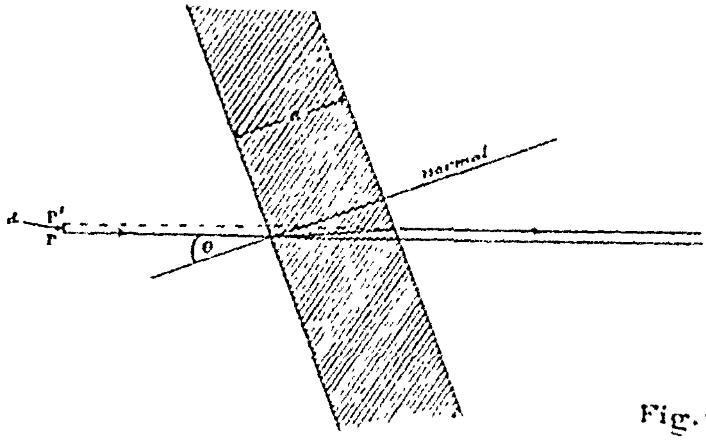

Fig. 4.

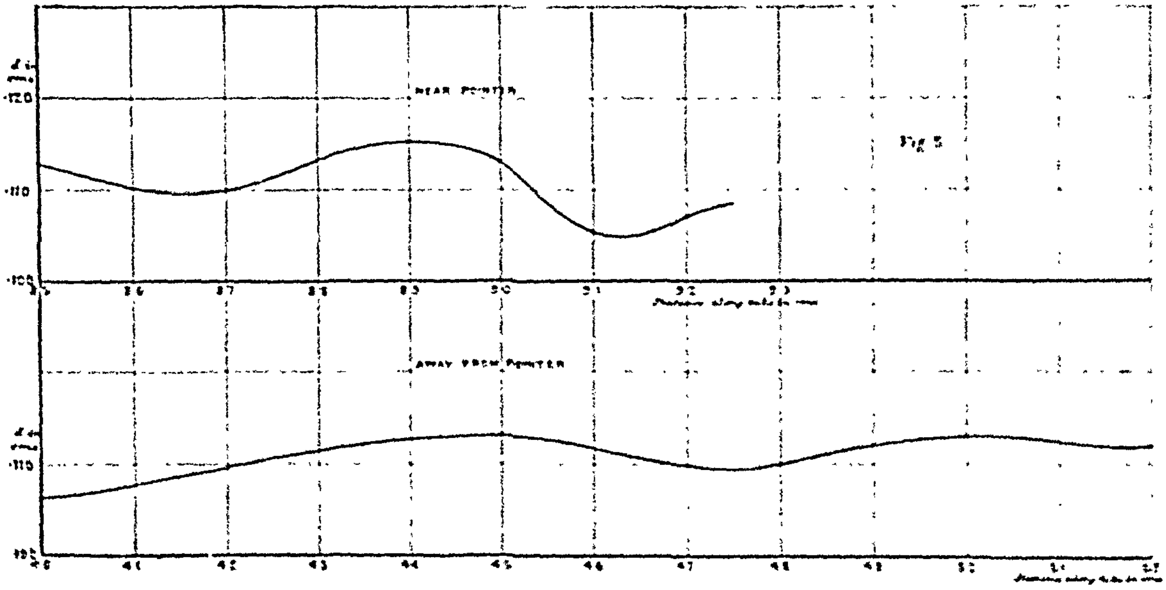

Fig 5